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OPTICAL THIN FILM COATINGS

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20. Abstract

Results of a survey on optical thin film and substrate technology conducted by the European Office of Aerospace Research and Development are reported. Over thirty university, commercial, and government laboratories were visited in ten Western European nations. Specific subject areas include design, synthesis, and characterization of optical thin films, substrate preparation and testing, and production of equipment for thin film deposition. Summary section indicating the most significant efforts and general state of optical coating research in Europe is included.

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This report has been reviewed by the EOARD Information Office and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

Armen E Mardiguian

ARMEN E. MARDIGUIAN
Captain, USAF
Chief, Physics

FOR THE COMMANDER

Winston K. Pendleton

WINSTON K. PENDLETON
Lt Colonel, USAF
Deputy Commander

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INTRODUCTION

This report on optical thin film and substrate preparation technology in Europe has been prepared by the European Office of Aerospace Research and Development (EOARD) at the request of the Air Force Weapons Laboratory (AFWL). The survey on which the report is based was conducted by the authors during the latter half of 1980 and the first half of 1981. Major James Fenner, a USAF Reserve Officer attached to EOARD, concentrated on a review of relevant literature and visits to some facilities in West Germany. Captain Armen Mardiguian, EOARD's Chief of Physics, visited organizations throughout most of Western Europe. Over thirty university, commercial, and government laboratories were visited. In addition, we identified several other organizations which are active in the area of thin films and substrate preparation which we were unable to visit due to time limitations.

Besides the AFWL, we have been in close contact with some other DOD laboratories which are working on optical thin films: the Avionics Lab and the Materials Lab of the Air Force Wright Aeronautical Laboratories, and the Naval Weapons Center at China Lake. These groups have provided much of the background information which was required to get our survey off the ground. This report should be of direct interest to these organizations, and may contribute to programs at several other DOD labs.

The remainder of this report is organized in five sections: a review of the work at the European laboratories we visited, arranged

by country (and indexed by topic); a short summary of the relevant activities at organizations we did not visit; a discussion of what we believe are the most significant efforts in Europe; and some observations on the general state of research, development, and production of optical thin films and substrates. The final section will address those areas for which some further action is desirable.

SECTION II

OPTICAL SURFACES AND THIN FILMS AT THE ORGANIZATIONS WE VISITED

In the course of our survey, we visited groups in ten European nations. Activities included design, synthesis, and characterization of optical thin films, substrate preparation and testing, and production of equipment for thin film deposition. The organizations are listed in alphabetical order in Appendix A, including addresses, phone numbers and principal contacts. For each visit, either a trip report or a memo for the record was prepared. These reports contain more detail than is included in this document, so if specific information is required, you may wish to contact EOARD for copies of the appropriate reports. A list of the reports and memos is given in Appendix B.

The remainder of this section is organized by country. Each organization's activities will be briefly discussed; some background will also be included.

Austria

Technical University of Vienna. The Institute for Physical Electronics, headed by Professor Arnold Schmidt, specializes in experimental solid-state physics using laser spectroscopic measurements. These include nonlinear techniques in III-V and II-VI semiconductors and in glasses. The Institute has also been active in developing tunable sources of subnanosecond pulses for their own diagnostics. Among the measurements that have been made are nonlinear absorption

in glasses and nonlinear optical susceptibilities in III-V materials and in CdS.

The most interesting work is related to a combination of two techniques: nonlinear spectroscopy and photoacoustic detection. This is only the second time that two-photon absorption has been measured in a solid using the photoacoustic effect. Several glasses have been examined, and preparations are under way to study CdS at liquid helium temperatures. Professor Schmidt is also hoping to make some room-temperature measurements.

Belgium

State University of Mons. Professor J. van Cakenberghe of the Inorganic Chemistry Department has patented a thin film deposition technique which uses a plasma source for high deposition rates (several microns/minute) at low substrate temperatures (100°C). An rf-induced discharge produces an oxygen plasma, which both sputters and reacts with the material to be deposited. Several types of oxide thin films have been grown on glass and plastic substrates; the films possess characteristics of sputtered and evaporated coatings. This technique was licensed to CIT-Alcatel, the French manufacturer of high vacuum and thin film deposition equipment; they have since sold the license to the Optical Coating Laboratory, Inc. (OCLI) in the US.

OCLI is now supporting Professor van Cakenberghe's work on a modification to the process, in which the plasma is formed by a dc discharge. An evaporated material reacts with the oxygen (or fluorine)

plasma to produce the oxide (or fluoride) molecule which coats the substrate. The high deposition rate and low substrate temperature of the original technique will still be present. By biasing the substrate, the deposition rate and film thickness can be accurately controlled.

Denmark

Optisk Laboratorium. The Optisk Laboratorium is a non-profit organization which is part of the Danish Academy of Technical Sciences. The Laboratory acts as a consultant to industry and also produces a variety of optical systems, components, and thin film coatings. Several computers are used for design of optical systems and thin film coatings, including optimization of multilayer dielectric stacks, and to simulate performance of both coatings and systems. Mr. W. Olsen, head of the Laboratory, also hopes to automate the thin film deposition processes.

The thin films are produced in a thermal and an electron-beam evaporative system. ZnS and fluorides are usually deposited using the thermal source, while the e-beam system is typically used for oxides (SiO_2/TiO_2). Optical monitoring is used to measure film growth. Most of the coatings are for visible wavelengths or the infrared (to 2.5 microns); a SiO_2/HfO_2 coating for wavelengths near 200 nm is now being developed. Some research is also under way on scandium oxide. The thin film area is responsible for approximately 50% of the lab's research and 80-85% of the service activities (consulting and sales). Most of the coatings are fairly "standard": interference filters

(up to 53 layers), antireflection, beamsplitters, and cut-on or cut-off filters.

Characterization of coatings and components is all of an optical nature: spectrophotometry, plane wave interferometry (to $\lambda/10$), Fiseau interferometry (to $\lambda/100$) and modulation transfer function. There is a small shop for grinding and polishing using conventional techniques.

Speculating on future trends, Mr. Olsen feels that the laboratory's largest growth will be in the thin films and electro-optics areas. He is one of the few people with whom I've spoken who doesn't see much application for sputtered coatings; this probably reflects the nature of the lab's "products" more than anything else.

University of Århus. Dr. G. Sørensen of the University's Institute of Physics is a chemical engineer whose specialty is the modification of materials by ion-implantation. He has recently completed a study of ion implantation of Al and Mg into Cu, with the objective of reducing oxygen penetration into the copper substrate. The implantation prevents the formation of CuO (which is thermally unstable), in favor of $CuAlO_2$ which is a more stable oxide. This process may produce copper laser mirrors which will not thermally decompose, a significant advance. He has provided some samples to the AFWL.

Dr. Sørensen has also developed and patented a process called reactive ion beam mixing. The first step in the process is the deposition (from liquid or vapor) of a layer of material on a substrate; an ion beam is then used to "alloy" the surface layer to the substrate.

For example, $PtCl_4$ is deposited onto a copper substrate from a liquid organic solution. A Kr- or Ar-ion beam is then used to bombard the surface; the residual chlorides are removed by immersing the sample in the organic solvent. The result was an alloy of Pt-Cu on the Cu substrate. The same technique has been used with Si substrates, producing noble-metal silicides which may be of interest for computer memories. This ion-bombardment/alloying process is far superior to the more common thermal treatment, which usually only produces a pin-holed Pt surface layer. A similar process has been used to catalyze the deposition of materials into pores and cracks in metal surfaces.

Characterization of the various samples is performed using Rutherford backscattering, x-ray electron diffraction, and nuclear-reaction analysis. These techniques time-share the same accelerators that the Institute uses for ion implantation and other studies: three electron-impact ion sources (90, 250 and 600 kV) and three Van de Graaffs (2, 5 and 7 MV), plus a number of smaller ion sources.

France

CIT-Alcatel. CIT-Alcatel's high vacuum products include vacuum equipment, He leak detectors, and thin film deposition systems. Mr. J.-J. Bessot manages the last of these areas, which is itself made up of four product lines: evaporative coating systems, sputtering systems, plasma chemical vapor deposition systems, and etching systems. Production and some development takes place at Alcatel's facility in Annecy, near the Swiss border. Research is limited to some work in Marcoussis,

near Paris. Alcatel's literature mentions thin films for optics only in passing, but some of their equipment may be useful for optical thin films.

The smallest systems are primarily for research and development laboratories or batch processing applications. The simplest versions are purely thermal evaporation systems. However, the series is designed in a modular fashion, and rf magnetron sputtering targets can be easily added. Pumps can also be chosen to meet varying vacuum requirements or oil-free operation.

Sputtering systems are Alcatel's biggest sellers. Besides the rf magnetron system, there are also rf and dc diode systems with targets as large as 50 cm. A triode plasma gun is available for sputtering of special materials and alloys. Alcatel worked with Professor van Cakenberghe at the State University in Mons, Belgium to develop the sputter-arc process described elsewhere in this report. The latest development effort at Annecy is a two chamber, 300 mm sputtering system with an air-lock loading system.

Jobin-Yvon. A division of Instruments S.A., Jobin-Yvon produces a variety of precision optical equipment with the major emphasis on monochromators and gratings. They are first in the world in the production of holographic gratings; for all gratings, they rank second behind Bausch & Lomb.

Of more direct interest for this survey is their technique for optical replication. The process consists of three steps: producing a metal master, which is a "negative" of the desired optical surface;

producing the component by sandwiching a special epoxy between the master and a substrate; and depositing an optical coating (usually gold or aluminum) over the epoxy. The critical factors in the process include the stability of the master and the behavior of the epoxy. The masters, which have diameters of up to 50 cm, are stored in special ovens in a clean-room facility, and are coated to reduce adhesion to the epoxy. The epoxy is developed in-house to meet specific requirements: temperature and mechanical stability (to $\lambda/10$ in the visible); high adhesion to the substrate and no adhesion to the master; and environmental specifications. A space-qualified material was developed for the Exosat x-ray mirrors, which are replicated on a beryllium substrate. Many of Jobin-Yvon's larger gratings are also produced by replication, both in France and at their subsidiary in the US. All the masters are produced by the facility in Longjumeau, near Paris.

A small amount of optical coating work is performed, mostly of metals (Au, Al, Pt) onto holographic gratings; occasionally, dielectric materials are used as antireflection coatings on ruled gratings. The latter films are typically MgF_2, but some oxides and other fluorides have been used. Jobin-Yvon has two Balzers box coaters and one bell-jar system. Both thermal and electron-beam evaporation are used.

Matra Optique. The Optics Division of Matra produces optical instruments and systems for commercial sale and to support Matra's Space and Military Divisions. Main product lines include equipment for photogrammetry, remote sensing, aerial reconnaissance, image processing, and metrology. The Division also produces a variety of

optical components, and provides optical coating and polishing services. Of the 280 people in the Optics Division, approximately 30 work in the optical coatings area.

The coatings group, headed by Mr. J. Guerain, was originally a separate company producing coating and testing equipment. They joined Matra in 1974 and shifted their emphasis to thin film research and production. Most of the equipment is either from Balzers or Leybold-Heraeus; Matra has recently ordered a sputtering plant from the latter. The range of products from the thin films group covers the spectrum from 30 nm to 20 microns; some of the more interesting include visible/Nd:YAG AR coatings and beamsplitters, AR coatings for 3-5 and 8-12 microns, UV laser coatings, and "very high energy" coatings for ruby and Nd:YAG lasers, having damage thresholds above 50 GW/cm^2 for 150 ps pulses.

Matra's research is mainly directed towards coatings for high energy lasers, and for military and industrial optics. Materials and processes constitute the bulk of the work. Iodine laser components are receiving special attention. Hard coatings on Ge and ZnSe are being developed for the French Ministry of Defense; most of Matra's commercially available coatings meet military standards for abrasion, adherence, humidity, temperature, and salt spray. Coatings for satellite horizon sensors (at 15 microns) are also being developed.

Characterization of coatings and components is performed by Matra's quality control center, which does some laser measurements, the environmental tests, interferometry, and spectrophotometry. Scattering

measurements are performed by Quantel and by Dr. Pelletier of the Center for Thin Film Studies at the University of Aix-Marseille. Damage threshold testing is done at the atomic energy laboratory at Limeil.

Recherche et Etudes d'Optique et de Sciences Connexes. REOSC was founded by Fabry and Chrétien in 1937 to study and build optical instruments. One of the first companies to produce thermal infrared photographs, they now specialize in precision optics, especially large astronomical components. Other important product lines include space optics for the visible and infrared, aspherical optics, and IR optical systems.

Their most interesting activity is the polishing of large optics. Polishing is performed using a full-size flexible wooden tool to produce aspheric surfaces up to 4 m in diameter with figure accuracy of $\lambda/33$. The largest component they have produced under contract is a fused quartz, 3.6 m primary mirror for the European Southern Observatory. They have produced many smaller components (1-3 m diameters) for astronomical applications, and are working with CGE Marcoussis on laser mirrors using a special Schott borosilicate glass. After a recent visit by representatives of the French and US military, REOSC has started work under a US Navy contract to produce a "medium" size (1.5 m) laser mirror. After polishing, the mirror will be coated in the US. REOSC does no coating of their components, but usually works with Matra or MTO (for metal or dielectric coatings). Component design is performed using a computer program from the University of

Rochester, while REOSC has written their own program to calculate the shape of the pitch working-surface on their polishing tools. They are following the Livermore work on bowl-feed polishing with interest; current rms roughness values are from 20 Å to 50 Å.

Characterization is performed optically and mechanically. Preliminary measurements are performed using rectilinear spherometers. Defects are checked using dark-field microscopy. Nomarski measurements are made for laser mirrors. Other diagnostics include Hartmann and null tests, wave shearing laser interferometry, and Lytle tests.

University of Aix-Marseille. The Center for Thin Film Studies, headed by Dr. E. Pelletier, is part of the optics group of the National Superior School of Physics at the University. The optics of surfaces and multiple layers is the center's forte. Thin film growth and characterization facilities are available for a variety of experiments, which can be categorized as: theory of thin film synthesis; production and characterization of multilayer dielectric coatings; and growth monitoring techniques.

Before the thin films are designed, the center must accurately characterize the materials in terms of optical properties such as refractive index and absorption. Dr. Pelletier is working with fairly well-known materials, among which are ZnS, MgF_2, cryolite, SiO_2, TiO_2, Ta_2O_5, and other oxides and fluorides. He produces single layers of these materials (of approximately 2 λ thickness) on transparent substrates, and then measures $T(\lambda)$ and $R(\lambda)$; reflectivity is measured at both the substrate and air interfaces. He is thus able to calculate

the material characteristics. The goal of the research is to match the theory and the films to within 10^{-6}. The layers are grown in an experimental, high vacuum evaporative system. Thickness monitoring for the experimental system is performed using quartz crystals and optical methods. Dr. Pelletier prefers the latter, and much of the center's recent work has been on the stability and sensitivity of different optical monitoring methods. Transmittance is measured by either of two sets of equipment: a grating (Czerny-Turner) spectrometer coupled to a photomultiplier, and a holographic-grating spectrograph coupled to a silicon photodiode array of 1,024 detectors.

Making best use of the optical data is itself a subject of study. Typical optical monitoring systems measure the transmittance of the film and stop the deposition when a "turning-point" is reached. This is accurate to only about 10%, but can be sufficient for quarter-wave stacks, since each subsequent layer compensates for the preceding layers. A more accurate method involves measuring the partial differential of the transmittance as a function of time. Dr. Pelletier has studied a third method, known as "maximètre", which measures the partial differential of the transmittance as a function of wavelength. These techniques may also be extended to non-quarter-wave layers. A summation is performed over wavelength of the difference between the experimental and predicted transmittance; the summation is calculated six times per second by a minicomputer for 256 wavelength values, using the data from the photodiode array. Such a system allows on-line synthesis of filters -- a real-time re-design of the coating.

The center is producing and testing several kinds of coatings: laser mirrors (primarily for ring-laser gyros), beamsplitters, narrow-band filters (Fabry-Perot components), AR coatings, and short-pass filters. These are mostly "classical" coatings -- two materials in quarter-wave stacks. Some unequal layer-thickness coatings have also been produced, but the primary effort has been and will remain the study of "classical" coating production technology. Two commercial coating systems are used, both of which were installed in special clean-rooms: a Balzers box coater, and a Leybold-Heraeus box coater. The latter is usually used only for ring-laser gyro mirrors. In addition to optical monitoring, oxygen pressure, temperature, and quartz crystal measurements are made.

Characterization techniques include reflectance and transmittance measurements for laser mirrors (to an accuracy of 10^{-4}) and scattering measurements for the gyro mirrors. The scattering apparatus is located in a special flow-box in a clean-room, and measurements are controlled by an operator at a PDP 11/03 in another room. Measurements are made as a function of angle in the plane of incidence; the sample can be scanned or rotated to give 30° and 45° angles of incidence (allowing measurements of scatter at the 0° and 180° points). The usual detector is a photomultiplier tube, but photon-counting techniques can also be used to measure picowatts of scattered light.

To support the work on scattering, the center is studying the structure of coatings theoretically and experimentally. Some of the theoretical work is on the correlation between interfaces in a

multilayer stack, comparing the rms roughness of each interface and the correlation of layers.

The latest major research topic is on non-homogeneous films, in which the index of refraction at any depth within the film is a function of the location. TiO_2 and SiO_2 layers have been studied; TiO_2 is deposited in a reactive process by evaporating TiO in the presence of oxygen. The research on TiO_2 was started because of its possible applicability to laser coatings (due to lower absorption); however, the effects of "graded index" coatings on scatter have yet to be determined.

University of Paris-South (Orsay). Dr. P. Croce's research at the Institute of Optics deals primarily with scattering in thin films and surface layers. Most of the films are metals with thicknesses comparable to an electron mean free path. Some dielectric films have also been studied, especially in conjunction with the French atomic energy laboratory at Limeil. Both theoretical and experimental studies are being performed. The research moves in two interdependent directions: better correlation of scattering to surface (or thin film) properties, and development of techniques to study surfaces by measuring scattering from (or through) the material.

Optical characterization techniques include reflection measurements using a HeNe laser, and transmitted or reflected scatter using the laser and a photomultiplier tube; effects of polarization are also measured. The surfaces are studied using Auger spectroscopy, x-ray diffraction, electron microscopy, and the Nomarski technique.

For metallic films, resistivity and work function are also measured. The Institute has installed a new x-ray system with a monochromator and goniometer which, by changing the angle of incidence of the x-rays, can be used to study surface roughness and dielectric constant.

Theoretical work focuses on calculations relating the angular dependence of scattering to the location of the scattering sites. Such calculations make use of Green's functions and vectorial methods. Some theoretical research has also been directed at explaining effects of local variations in the index of refraction of a surface. The theory ties in well with the Institute's experimental program. For example, calculations were performed for the scattering from a TiO_2 thin film, assuming both internal and external defects. Experimental measurements were then made; comparison with the theoretical calculations showed that the external defects alone could account for the results. This tends to confirm the importance of surface roughness as a source of scattering.

Other research combining experiment and theory is related to polishing phenomena. Analysis of mechanically polished surfaces has shown that surface layers are produced by the polishing process. On silicate glasses, for example, a low density layer of a few nanometers in thickness is formed above a second layer, tens of nanometers thick, that has a density higher than the bulk glass. The analysis compared polishing time, abrasive materials, polishing material (pitch vs. teflon) and other treatment of the glass, and correlated each to the properties of the layers. These properties were, in turn, determined from grazing

x-ray reflection measurements, using a theory relating the reflection to surface roughness and variations in dielectric constant.

University of Pierre and Marie Curie. The Laboratory of the Optics of Solids has a range of interesting research on optical methods, and Professor F. Abelès, director of the laboratory, is well-known throughout Europe for his expertise on thin film characterization. Most of the laboratory's work is in the area of metallic thin films; the US Army is supporting Professor Abelès' work on adsorption on metal surfaces, studied by optical techniques and Auger spectroscopy. RADC is also funding some work through EOARD for research on the relationship between structure and stability of metallic glasses.

Professor Abelès is often called upon by European organizations for consultation on thin film characterization and growth, and he represents a wealth of information on European thin film activities. The laboratory's diagnostics include ellipsometry, differential reflectivity and transmissivity, attenuated total reflection, and Auger spectroscopy. High vacuum systems are used for both thin film deposition (sometimes only monolayers in thickness) and characterization.

Federal Republic of Germany

Ernst Leitz Wetzlar GmbH. Leitz is a world-wide optical company, perhaps best known for photographic equipment. They also produce several types of optical thin film coatings, primarily for their own components. Most of the production coatings are deposited in Leybold-Heraeus systems; there is also one coater built in East Germany which

Leitz uses for single-layer metal films. (Compared to the other systems, the East German equipment seemed very unsophisticated, but very rugged.) Some sputtered films are produced on components for an acoustic microscope for which Leitz holds a license from the developer; the sputtering system is a Leybold-Heraeus product.

Research and development of thin films is the responsibility of the Thin Film and Filter Laboratory, headed by Dr. R. Ludwig. The Laboratory started research on MgF_2 coatings in 1952; they have since expanded their work over a wide spectral range and a large number of materials. Lately, they have been concentrating on IR coatings in the 3-5 micron range. Hard coatings for 8-12 microns are also of interest to the Laboratory.

Research coatings are produced with Leybold-Heraeus systems, most of which are fairly new and at least partially computer-controlled; there is one Leybold system which is 25 years old but still in use, and a small bell-jar system from Balzers. Research is performed for in-house development and on outside contracts, including mirrors for AIM missiles and antireflection coatings on germanium. Al_2O_3 films are also being used for cut-on filters in the infrared. Although Leitz has done some custom coatings work, a commercial coating service is not offered. Characterization is mostly performed by optical measurements using commercially available equipment such as spectrometers; some scattering and interference measurements are also made.

Asked to speculate about future developments, Dr. Ludwig mentioned increased work on imager materials and coatings for the 8-12 micron

range, and an attempt to find a substitute for ThF_4 (perhaps YtF?). Other materials don't seem to be too much of a problem; Leitz currently buys almost all their material from Merck, the German chemical company.

Fraunhofer Institute for Applied Solid State Research. The Fraunhofer Gesellschaft (FhG), established in 1949, is a society for the advancement of applied research. The Institut für Angewandte Festkörperphysik (IAF), one of 23 FhG scientific institutes, is composed of six departments, working on solid state physics and chemistry; infrared, microwave, and display physics; and process technology. The IAF's activities in optical thin films and surfaces is mostly performed in the solid state chemistry department. The department, headed by Dr. P. Koidl, is really in the materials science business. Three applications are addressed: passive IR materials, electro-optical and nonlinear optical crystals, and laser materials. The majority of the work in IR materials is on ZnSe for windows; they are also interested in materials for multilayer dielectric coatings and amorphous carbon coatings. However, growth of optical coatings at IAF is only just beginning. IAF has a thermal/electron-beam evaporative system, and will use an rf plasma-activated deposition for the carbon films.

Of more immediate interest are the department's characterization facilities. Transmission and reflection can be measured between liquid nitrogen temperature and room temperature. IAF also has a CO_2 laser calorimeter which can map a component or thin film with a resolution of 50 microns. Thin film structure and impurities are studied using

scanning electron microscopy, x-ray photoluminescent spectroscopy, x-ray diffraction, and secondary ion mass spectrometry. IAF is working with Professor G. Busse in Munich on depth-resolved photo-acoustic spectroscopy. They have also implemented a coupled mode method (as opposed to the usual matrix method) for their software which calculates the physical location of absorption centers. Other diagnostics are used for the study of oxide layers on semiconductor materials: low-energy electron diffraction and residual gas analysis. These can also be employed for characterization of the optical thin films.

Leybold-Heraeus GmbH. Leybold-Heraeus is one of two companies that dominate the European market for optical thin film deposition equipment. The Vacuum Process Engineering Division has three departments concerned with coatings: large machines, small machines, and development. The first of these builds large coating systems for production-line applications such as depositing metal films on plastic in a continuous process. The small machines division produces coating systems for optical and electronic coatings; they manufacture a wide range of computer-controlled box coaters and peripheral equipment. The development department is responsible for research and development of new coating processes, equipment, materials and special coatings.

The precision optical coatings group, headed by Dr. H. Schwiecker, concentrates on optimization of thin film deposition techniques and software. The group is using an evaporation system and a sputtering system.

The evaporative coating system is a Leybold-Heraeus one-meter box coater with two electron beam and two thermal sources. Since it is currently being used to test new software programs for the control system, the coater is very well instrumented with manual and automatic controls, quartz and optical monitors, pressure and temperature sensors, and several other pieces of diagnostic equipment. The heart of the automatic control system is a computer/display module produced by Inficon Leybold-Heraeus Inc. (a US-based company). It is the software for this system that is being developed in the optical coatings group. Software packages are transferred to the manufacturing groups for sale with coating systems.

The process photometer, which is tied into the controller, can be programmed by hand or by the computer to monitor the film growth and close shutters at predetermined points. It can also perform automatic thickness compensation, and provides time and wavelength information.

The experiments currently under way with the sputtering system are related to optimizing the deposition process. The substrates are mounted on an annular ring which rotates past the sputtering targets. Dr. Schwiecker is studying rf sputtering of SiO_2 and Ta (using oxygen for a reactive deposition). Some experiments on magnetron sputtering will be attempted this summer. The rf sputtering system may be commercially released by Leybold-Heraeus in several months; the models now available are dc or high-frequency cathode sputtering systems better suited to electronic or mechanical coatings.

Aside from the in-situ monochromator measurements, Leybold-Heraeus has built a spectral analyzer for measuring their coatings. Measurements of transmission (T) and absorption (A) to within $\pm$ 0.01% and integrated scattering (S) to $\pm 10^{-5}$ are performed using an optical system which includes argon-ion and helium-neon lasers.

Among the optical coatings they have produced in their experiments are rangefinder-type "double-dip" antireflection coatings (with close to zero reflection at both visible and YAG wavelengths), and laser mirrors for HeNe and YAG wavelengths. Typical figures for the TiO_2/SiO_2 multilayer mirrors are R = 99.78%, A = 0.1-0.12%, S = 0.06%, and T = 0.04%. No coatings are sold commercially; however, Leybold-Heraeus is entering into a cooperative agreement with a sister company, W. C. Heraeus, to help them produce precision optical coatings for sale.

Asked to predict the future trends in optical coatings, Dr. Schwiecker placed his interest in three areas: the demise of quarter-wave stacks, coevaporation and controllable index of refraction, and sputtered coatings.

Optische Werke G. Rodenstock. Rodenstock manufactures large numbers of optical components, including some high precision optics for military and graphic arts applications. Thin films development is limited to the technology group, which operates two small bell-jar coating systems and a modest collection of optical characterization equipment. Rodenstock does produce AR coatings for their own lenses in the visible wavelength region, and does some 3-5 micron AR coatings as well. However, the majority of their IR components are coated

elsewhere: Balzers, OCLI (Scotland), Matra, Société Anonyme de Télé-communications, and MTO (France).

The R&D group, led by Dr. Paul Kuttner, is made up of four sections: optical design, mechanical design, physics, and optical testing. The last of these sections is responsible for producing and operating the equipment required to evaluate Rodenstock's precision optical products. The most interesting of the techniques is the measurement of the homogeneity of IR materials. Values of the index of refraction and the spatial derivative of the index are measured; changes in the index of less than 1 x 10^{-4} are resolvable.

Other measurements of coated optics are primarily conducted by the military optics group. These include erosion, salt-spray, heat, thermal shock, spectrophotometry, integrated scattering and scratch tests. Military products include IR lenses for seekers, thermal imagers, and IR domes for the Sidewinder.

Technical University of Hannover. The Institute for Applied Physics, under the direction of Professor H. Welling, studies new lasing media and techniques, and applications for lasers. Dr. J. Ebert is the head of the evaporation group, which was set up to provide optical thin film coatings for the Institute's research. The group has expanded to produce coatings for organizations outside the Institute.

Dr. Ebert's group has three specialties: UV mirrors; high power laser coatings for ruby and Nd:YAG; and low scatter mirrors for HeNe laser gyroscopes. There is also some work on laser-damage measurements as part of a PhD program. Many other coatings are being studied

(or produced) to a lesser extent. The group has two coating systems: a Balzers bell-jar thermal evaporation unit and a Leybold-Heraeus box coater with two electron-beam sources. The former system is primarily used for soft coatings such as ZnS, the latter for hard coatings. Both are located in a clean-room to reduce dust problems, especially for the gyroscope mirrors. Over 20 materials have been used for coatings in the spectral range from 180 nm to 20 microns. Coating measurements include spectrometry, an integrating-sphere scatterometer (accurate to $\pm 10^{-5}$), and a laser calorimeter for absorption (temperature variations are measured by thermistors on the sample and a reference to within 10^{-3} K°; accuracy is limited by scattering).

The work on UV coatings is aimed at preventing the decomposition of the materials during deposition. Evaporation is therefore performed in a 10^{-4} Torr oxygen atmosphere. An ion gun is used to inject O_2^- or O_3^- which is produced in a hollow cathode glow discharge operating at a pressure of a few millibars. Dr. Ebert has produced BeO/SiO_2 coatings capable of withstanding KrF laser intensities of several GW/cm^2. Such a coating, tested at Los Alamos Scientific Laboratory, showed the highest damage threshold so far measured at LASL. In-house applications include color center, excimer, and alkali dimer lasers. Dr. Ebert's group also produces the coatings for Lambda Physik's excimer lasers.

In-house damage threshold tests are performed using either of two Nd:YAG lasers. One laser produces a single 10 ns pulse of 60 mJ; the second laser, which is more frequently employed, produces a train of

about twenty 100 ns pulses of 50 μs separation, with a maximum of 200 mJ/pulse. The maximum power density is approximately 5 GW/cm^2. The pulses are nearly Gaussian in profile, and are focused to a 0.5 mm spot. The moment at which damage occurs is determined by measuring the transmission of a He-Ne laser beam through the sample.

Dr. Ebert is working with Balzers to suppress retroreflection of ring-laser gyroscope mirrors. His approach is two-pronged: to reduce microdust in the coatings, and to control the grain size. By using strict clean-room procedures, Dr. Ebert has produced TiO_2 coatings with 0.08% scatter. To reduce grain size, low temperature (50-80°C) deposition of Ta_2O_5 has been performed, followed by a higher temperature annealing step. Coatings produced by this technique have demonstrated scattering of 0.02-0.03%, absorption of 0.01%, and reflectivity of 99.96% (s-component, 30° angle of incidence).

Liechtenstein

Balzers Thin Films Division. Balzers is probably the best known name in optical coatings and high vacuum equipment in Europe. They produce high vacuum components, thin film deposition systems, and optical thin films. The product divisions interact to a significant extent, though the Thin Films Division must decide which processes they will license through the deposition systems division, and which they will maintain for their own commercial production and sales. This forces the Thin Films Division to constantly develop new coatings and techniques in order to remain ahead of the technology available

from other Balzers divisions. The result is a significant investment in new deposition techniques and an emphasis on high quality coatings. These are available on substrates provided by Balzers or by the customer. Products include (but are not limited to) AR coatings for the UV through the IR, beamsplitters, and laser coatings (AR, mirrors, and polarizers).

The quality assurance group concentrates on technical aspects of thin film quality. Dr. Karl Guenther, head of the group, is well known by other European thin film groups for his concern with the effects of substrate preparation. This reflects his conviction that high quality coatings cannot be supplied unless the substrates provided to Balzers have well-prepared surfaces. In addition to this commercial interest, Balzers is working on low scatter mirrors for ring-laser gyroscopes and other systems, and they are well aware of the dependence of laser damage thresholds on substrate quality.

The group has a small bell-jar coater which they use for studies of the coating process (e.g. the effects of charging during electron-beam evaporation). They employ visible and ultraviolet ellipsometry and an integrating sphere scatterometer. A Balzers ion-etcher has been combined with a quadrupole mass spectrometer to perform evaluations of thin film constituents. A new facility for evaluation of laser damage thresholds is being considered. Dr. Guenther has recently added an optician with approximately 30 years experience to his group to study "superpolishing" of substrates. A temperature- and humidity-controlled room has been set up to make a systematic approach to polishing and characterization.

The development department employs approximately 25 people. Their primary objective is to develop new coatings and processes: laser coatings, infrared coatings, organic coatings, electrochromic materials, and general process optimization. Dr. Werner Thoeni, the head of this department, emphasized that the development work supports the Thin Films Division, with indirect interaction with the other Balzers divisions. Research on process optimization is mostly experimental, and includes materials as well. (The Swiss Government, which administers some functions of Liechtenstein, has forced Balzers to discontinue the use of ThF_4.) Low scatter coatings receive much of the emphasis in this work. Evaporative processes are the primary technique, though some sputtering technology has been studied.

Laser-coating research concentrates on ultra-low scatter optics; Balzers has Ministry of Defense contracts related to British and French laser gyroscopes. Infrared coatings are primarily antireflection thin films for applications such as forward-looking infrared systems.

Optical characterization includes IR, UV and visible reflectometry and scattering measurement (using an integrating sphere). Substrate and film structure is studied in several ways: scanning electron microscopy with an energy dispersive x-ray system; electron diffraction (in transmission or reflection); secondary-ion mass spectroscopy and Auger spectroscopy (with an ion-etcher); and mechanical measurements (Talystep and Alphastep equipment).

The Netherlands

NV Optische Industrie de Oude Delft (Oldelft). Oldelft produces advanced optical and electro-optical instruments and systems. Their earliest work was on x-ray cameras for medical use; similar products still account for 20% of the business. The remainder consists of image intensifiers and rangefinders. All their research and development is in some way related to these products.

Oldelft looks at coatings as a means, not an end. Nevertheless, they produce a variety of thin films and they are performing research on several more. Their earliest coatings were for ruby lasers; Oldelft produced 15 types of ruby-laser rangefinder systems. In the mid 1970s, they worked with the Dutch and Italian Air Forces on thermal imaging systems. They are currently cooperating with Philips on rangefinder systems for German armor; however, Oldelft typically is more interested in airborne systems. Thin film coatings currently produced include military-qualified Al and Ag on metal mirrors; AR coatings for 400-900 nm (image intensifiers), 1.06 micron (Nd:YAG), and 8-12 micron (IR imagers); and low-power laser beamsplitters.

The Nd:YAG coatings are resistant to power densities of 700 MW/cm^2 (in 20 ns, 50 MW pulses). The research department is pushing the threshold to 1 GW/cm^2. The beamsplitters are also to be optimized for higher thresholds. Research on "double-dip" AR coatings (for visible plus Nd:YAG wavelengths) is aimed at reducing reflection in the visible (440-740 nm) to less than 1%, with an average value of 0.5%. Other projects involve new materials, computer-design of optimized coatings, and ion-milling for room temperature depositions.

Past work included an investigation of the effects of inhomogeneous refractive indices in multilayer coatings.

The research department has a few Balzers bell-jar systems and a Leybold-Heraeus box coater, which is also used for production of MgF_2 coatings. Characterization of the coatings and components is primarily optical: a Nd:YAG laser which can be used for damage-threshold testing or for transmission/reflection measurements; scattering (also used for research on polishing quality); interferometry; and modulation transfer function (MTF) measurements. Oldelft is making MTF measurements on single-point turned germanium aspheres produced by Philips.

Philips Research Laboratories. Philips is a multinational company with eight research labs in the Netherlands, Belgium, France, Germany, England, and the US. Fifty percent of the research is concentrated in the laboratory in Eindhoven, which employs 2200 people (530 university-trained scientists and engineers). There are four departments at the laboratory: Physics, Applied Physics and Mechanics, Electronic Systems, and Materials. The Optics Group, led by Dr. Jan Haisma, is part of the Applied Physics and Mechanics Department. The group is working on single-point turning of optical glass, machining of metals, and optical coating. The optical coatings research is primarily military in nature, dealing with infrared coatings.

Dr. Haisma's research on metal machining and on single-point turning of glass is mainly related to the production of aspherical optics. In 1976, Philips started investigations of the direct machining of optical glass. The first experiments, performed at room

temperature, were unsuccessful. Higher temperature processing has produced better results.

The turning is performed on a precision optical lathe developed at Philips, called COLATH. It is a computer-controlled, two-axis machine. Glasses are heated to near their "American softening point" using a slit burner; the temperature at the machining point is stabilized to $\pm$ 2°K using an IR vidicon with feedback to a point-burner. A hafnium-nitride coated metal tool produces the best results. Turning must be done within 20°K of the softening temperature. Above this, the glass is too soft; below this, it is too brittle. At the proper temperature, the turning process produces a continuous glass chip. Many glasses have been studied, though ultra-low expansion glasses have not been investigated. Surface precision is typically two microns, producing a diffuse surface. Transparent surfaces have been produced by optimizing the machining process.

Diffraction-limited optics can be produced, but the process is time-consuming and expensive. Molding of the components would be a significant advance -- Philips is working with an unnamed US company to produce molded aspheric optics. The molds will be provided by Philips; research on their production has involved the machining of hardened steel, and has been going on for some time. Using the COLATH, the steel molds can be finished to 100 Å, with a precision of 1000 Å. If this cooperation is successful, Philips will be using molded aspheric optics in their commercial equipment in the near future.

Sweden

AGA Optical. AGA Optical is a financially independent company within the large AGA group. It was founded in 1975 when AGA Innovation, the AGA group's central laboratory, was broken up. At the time of its formation, AGA Optical faced an immediate and difficult problem: to reorient their output from research and development to production. Much of the pure research was dropped, and the number of employees decreased from 45 to 30 as some of the people interested strictly in research departed for universities and other research centers.

Their first coatings were primarily AR coatings on Si and Ge for AGA Infrared Systems, a sister company. The product line has since expanded to include AR coatings in the visible and 8-12 micron regions, V-type and dual-wavelength AR coatings, laser mirrors, filters for ultraviolet-infrared wavelengths, and beamsplitters and combiners. Coatings are produced on customer-supplied substrates and on their own substrates. AGA Optical does not have a separate R&D group, since all their work must still be project-oriented (i.e., "technically useful" to a product). However, they do cooperate with Swedish universities by providing topics and facilities for students working on MS degrees, somewhat like the US "co-op" programs.

Dr. R. Jacobsson, President of AGA Optical, places the development emphasis on materials and processes, but there is some work on mechanical properties of thin films and a study of the adhesion probabilities for single atoms or molecules. His highest priority is materials characterization and data documentation. AGA Optical has established

an in-house data bank of thin film optical properties, similar to those at NRL and Fort Belvoir or the NWC reflectance data. Optical characterization performed in-house includes ultra-high vacuum (10^{-11} Torr) measurements of reflectivity and transmittance (using the NWC method), photometry as a function of incident angle (to measure index of refraction and film thickness), scattering (by the double beam technique), and spectrophotometry. Scanning electron microscopy and x-ray fluorescence measurements are performed by outside groups.

Studies related to deposition processes are primarily aimed at optimization of the process itself. Some work is also performed on mass-spectrometry of the vapor in the coaters, using an on-line system built in-house; calculations of the vapor distribution from the source; and a study of sticking probability as a function of substrate temperature (on quartz substrates). AGA Optical is investigating the mechanical properties of thin films by three techniques: on-line stress measurements using interferometry, adhesion by the direct-pull method, and erosion tests. The stress measurements are performed using the Perkin-Elmer technique and a temperature-compensated Michelson-type interferometer.

AGA Optical has ten box coaters, most of which are from Balzers; the largest, a 1 x 1 x 1.5 m unit, was first built by Balzers to AGA Optical's specifications, and has since been marketed to several other companies. The thin film deposition processes are not licensed from Balzers, but are developed in-house. Debugging and modification of the coaters is also an in-house project.

Institute for Optical Research. The Institute had a large optical coatings program in the past, and many members of AGA Optical were trained at the Institute, which is jointly funded by the Swedish Government and industry. Research emphasis has shifted, however, and the only current thin films work is related to solar cell coatings. Two research deposition systems are available, one having a thermal evaporation source, the other an electron-beam evaporation source.

Switzerland

Battelle Research Center. Dr. B. Zega has done quite a bit of work on coating of materials, and his current research in reactive magnetron sputtering is of possible interest for optical coatings. He and his co-workers have studied high deposition rate processes (e.g., one micron of molybdenum/minute), and have developed special magnetrons for coating the interior of parts (e.g., the inner diameter of ring-shaped objects). Dr. Zega holds a patent on a "self-protecting" magnetron target system (using a helium leak detector) which will shut off the magnetron within a millisecond after the target has developed a hole due to the sputtering. There has also been some research on reactive ion plating for hard, high-adhesion coatings. Unfortunately, none of these techniques has been optimized for optical coatings, and Dr. Zega does not foresee any work in that direction.

United Kingdom

Barr & Stroud, Ltd. Barr & Stroud is well known throughout Europe for optical coatings and components, including laser rod and IR transmitting materials. Many of these components support a large range of military products, including laser designators, rangefinders, and periscope optics.

The thin films research and development group, headed by Mr. B. Monachan, consists of approximately fifteen scientists and technicians, whose activities include design, growth, and characterization of several types of coatings. The facility employs several coating systems. In addition to two older Balzers evaporative coaters, a new Balzers cryopump unit has recently been added. It includes a Temescal electron-beam source, quartz and optical monitors, and an rf quadrupole mass spectrometer. Laminar flow modules are being installed on these systems. Two sputtering units are used for research on durable coatings, including hard coatings for germanium windows, and coatings for alkali-halide substrates.

The characterization capabilities are limited, but are being augmented by new staff and equipment. Present diagnostics include Nomarski techniques, scattering measurements at He-Ne wavelengths, cavity-loss reflectivity measurements, calorimetry (at 10.6 microns) for absorption, and a Tencor scanning profilometer. Calibration standards for the profilometer have been supplied to Barr & Stroud by the Drs. Bennett at the Naval Weapons Center, China Lake. New diagnostics will include spectrophotometry, and absorption, scatter, and damage threshold measurements at 1.06 microns. Damage threshold measurements are presently

performed by the GEC Hirst Research Centre, where some vacuum and air calorimetry measurements are also made.

The research group is primarily involved with coatings on ZnS and ZnSe substrates. Antireflection coatings have been developed which display 98.4% transmission and 0.7% reflection at 10.6 microns; coatings for 1.06 micron have 98.8% transmission and 1.0% reflection. Hard coatings for CO_2 laser components are also receiving significant attention.

Surface preparation facilities serve both the research and production groups. Almost all the work is conventional polishing, with a small amount of diamond fly-cutting for Ge and Al substrates.

The production group, headed by Mr. J. Allen, operates over twenty coaters (not including the research systems), primarily Balzers and several new Electrotech units. Many of these are microprocessor-controlled. Aside from a range of coatings for customers, there is a large in-house requirement for coated components. These include military laser systems (ruby and Nd:YAG rods for rangefinders), and antireflection coatings on germanium, silicon, arsenic trisulphide, and chalcogenide and calcium aluminate glasses.

The research and production groups will be moving into new adjoining facilities in the next few months. Mr. Monachan was optimistic about the time which would likely be lost during the relocation. The research group will maintain their interest in hard coatings, and in bringing the new diagnostic equipment on-line. In addition, more effort will be expended on high laser damage-threshold coatings. Many

of their laser rods are presently sent out for coating by CVI Laser in the US and TecOptics Ltd. on the Isle of Man. Barr & Stroud would like to be able to coat these components in-house.

Ferranti Ltd., Professional Components Group. The laser coatings work in the Dundee facility has its roots in early Ferranti work which led to the first European HeNe laser in 1963. In 1968, low scatter mirrors were produced (using ZnS and cryolite) for ring-laser gyros. Ferranti acquired control of Laser Associates Ltd. in 1973, along with their personnel and expertise in high energy laser components and laser-damage resistant coatings. The laser group now includes sixteen scientists, though many of them do not work on coatings.

The coatings group has three thin film deposition systems: a Balzers 20" system (two resistance-heated sources, optical and quartz crystal monitors), an Edwards 19E 19" system (six resistance-heated sources, optical monitor), and a Genovac 12" glass bell jar used for studies of platinum evaporation. Diagnostic equipment includes three spectrophotometers, a Nomarski polarization interferometer, and absorption measuring equipment incorporating a Ferranti laser.

Antireflection, selective transmittance and high reflectance coatings are available as standard products. Ferranti also provides a repolishing/coating service for laser rods and other optical components. Between 60 and 70 percent of the coating work performed by the Professional Components Department is for in-house use, much of which supports the electro-optics group in Edinburgh. The remainder of the coatings are produced for other commercial firms, universities,

and government laboratories. Nearly all the coatings have been produced using evaporative techniques. A dozen dielectric materials and nearly as many metals have been used at one time or another. Substrates are primarily non-metallic (glasses, SiO_2, Ge, Si, ZnSe and GaAs), though they have also coated some diamond-turned copper substrates.

Mr. N. Forbes, manager of the Laser Group, indicated that the group is scheduled to expand to approximately forty people within the next few years, with the largest growth in the coatings area. Goals of the expansion are a general improvement in coating and surface preparation technology, with a parallel decrease in the role of technician-controlled processing. One specific target is "superfinished" surfaces for ring-laser mirrors (10^{-8} scatter). Among the steps to be implemented are better control of the coater environment gases, improved substrate preparation (including diamond-machining for IR components), and eventually a new coating "factory" incorporating Class 100 standards for the preparation and coating facilities, Class 10,000 for the inspection area.

The first step in this renovation includes installation of three new Balzers coating systems. These systems will incorporate electron-beam and resistance sources, optical and quartz-crystal monitors, a mass spectrometer for gas analysis, and microprocessor control. One of the systems will be fitted with an Ion Tech neutral ion beam milling facility.

Newcastle upon Tyne Polytechnic. The thin film devices group at the Polytechnic was set up several years ago by Mr. Angus MacLeod, who

has since moved to the Optical Sciences Center at the University of Arizona. Most of the group's work is on growth monitoring and film pore size distributions.

The fairly small program on optical coatings, run by Dr. R. Hill and Dr. M. Bowden, is both theoretical and experimental. The theoretical program is a study of effects of film structure at high packing densities. Many grain shapes have been modelled, assuming air or water in the pores. One of the PhD students has been developing two-dimensional finite element techniques to examine the electric fields in the films as a function of packing density and grain shape. Index of refraction and water absorption are not strongly affected by grain shape; the electric field calculations show a higher sensitivity. Factors of five between neighboring maxima and minima have been found, with the neighboring grain playing the largest part in the contours of the field. Further work is planned, including an expansion of the calculations to three dimensions (the 2-D calculations assume a slowly changing index of refraction, and so are not accurate at interfaces). Almost all the computer work is performed at the Rutherford Laboratory. Close cooperation with Dr. E. Pelletier (University of Aix-Marseille) is also maintained.

Experimental work includes studies of the change in optical properties with time as a coating is exposed to air, and a program on ion-plated coatings. The former work is performed on a Balzers 560 coater; reflectance measurements are made using a steerable optical fiber. The data are intended to back up the theoretical work (and

to acquaint the students with the hardware end of coatings). A dc discharge has been used, in contrast to the more typical rf techniques; energy is in the hundreds of eV range. The ion plating method should produce denser, harder coatings, since the growth does not require nucleation sites. Of the many materials tested, ZnS showed the most improvement compared to evaporative coatings. Oxide films displayed less change.

While there has been some reduction of interest in ion plating with the introduction of diamond-like carbon coatings, the Polytechnic is working on a Ministry of Defence grant to produce hard coatings on germanium windows/sensors for surveillance systems.

Queen's University, Belfast (QUB). Professor P. Lissberger directs the University's thin film optics group. The group is divided between production of research-oriented optical thin films, and the characterization of these films. In addition, applications-oriented coatings are produced for in-house and outside users by the Optical Services Unit, run by Mr. D. Moore.

Professor Lissberger has developed a microprocessor/coater system which controls the film thickness based on a least-squares fit to a quadratic shape. Data from constant monitoring of the films during growth is fed into the microprocessor system; this allows prediction and control of a film growth, an improvement over the turning point technique. A newly built ultra-high vacuum coater has been built for growing coatings with lower impurity levels. It should operate near 10^{-10} Torr, compared with 10^{-6} to 10^{-5} for his present coater. The new coater will be used primarily for coating research.

The coatings grown by the thin films group cover a variety of potential applications, though the majority are for studies of film properties. Multilayer dielectric stacks have been produced as enhanced-reflectance coatings, narrow-band filters and polarizers. Hard coatings have been produced using MgF_2 and cerium compounds. The properties of these various coatings and films are being investigated, with the objective of obtaining a better understanding of the factors which limit their performance. The results of the characterization are then related to the parameters governing the deposition of the coatings, and changes in the deposition parameters are made to produce an improved coating. This process is backed up by theory regarding the deposition itself and atomic models of the coating materials and optical phenomena.

Characterization of the coatings is performed for both optical and structural qualities. Two automated ellipsometers have been built by the thin films group. No phase plates are used; rather, a Faraday cell is located on both arms of the ellipsometer. The dc Faraday cell on the output arm rotates the place of the polarization as the phase plate normally would. Modulation of the current in the Faraday cell allows lock-in techniques to be used. Accuracies of one part in 10^5 are achieved, and 4000-5000 readings can be taken in a few hours. Photo-acoustic spectroscopy research in the laser group may also be applied to the characterization process.

The newest diagnostic is a laser calorimeter for absorption measurements. A dye laser will heat the substrate and coating if

absorption is present. A He-Ne laser will be reflected from the uncoated back of the sample to measure expansion. Dr. R. Atkinson, who is developing the system, hopes to achieve accuracies of 10^{-4} K°. Other diagnostics include a transmission electron microscope for examining coating structure, and a Taylor-Hobson "Talystep" which uses a diamond stylus to measure film thickness (5% accuracy at 20 Å).

The Optical Services Unit operates five coaters. Two Balzers systems are used pri-arily for multilayer stacks on substrates up to two feet in diameter. Coatings have been produced for several users, including the Rutherford Laboratory's six-beam inertial fusion laser (IR polarizers), the QUB 0.3 terawatt laser (turning mirrors), and the QUB space group (UV filters). Three smaller coaters are used for deposition of metal films, primarily aluminum.

The QUB 0.3 terawatt Nd:YAG laser has provided some operating experience on laser damage to components in the optical train. The system uses mirrors produced by the Optical Services Unit and polarizers bought from CVI Laser, Inc. in Albuquerque, NM. None of the multilayer dielectric mirrors has suffered any detectable damage. Power levels of 2-3 GW/cm^2 and energies of 3-4 J/cm^2 have not damaged the final turning mirror. However, some problems have occurred with the polarizers.

Professor Lissberger's group is designing a polarizer coating to be used in the terawatt laser, similar to those made for the Rutherford Laboratory. In contrast to other theories, Professor Lissberger feels that such coatings for high energy lasers should be deposited in tensile

stress, so that heating by the beam will decrease the stress in the coating.

Technical Optics, Ltd. TecOptics is a small company which was founded and is run by brothers D. and M. Lunt, both of whom have extensive experience in optical coating technology. TecOptics is divided into two groups, the Optical and Instrument Divisions. The Instrument Division produces primarily optical equipment: Fabry-Perot interferometers, tunable filters and etalons, optical spectrum analyzers, fixed narrow-band filters and etalons, and electronic control units. The Optical Division markets a wide range of high energy laser optics, with high damage thresholds being the primary concern. Price list items include high-reflectance and 'V' antireflection coatings, guaranteed to withstand 50 GW/cm^2 (50-100 ps pulses), 10 GW/cm^2 (ns pulses), and 3.5 GW/cm^2 (30 ns pulses).

TecOptics has chosen the ZrO_2/SiO_2 system for use in all their commercial coatings. This combination yields high damage thresholds, ultra-hard surfaces and low losses over a wide range of wavelengths. The coatings exhibit scattering and absorption losses as low as 0.08% total for a 27 layer stack; the low scattering value makes these coatings well suited for laser gyro systems. In fact, TecOptics is supplying mirrors for Singer-Kearfott gyros. Other products include high power plate polarizers and broad band antireflection coatings. Their coatings are used by the Rutherford Laboratory high energy laser facility.

Coating equipment includes three microprocessor-controlled Bendix-CVC coaters, two 18" systems and one 24" system, which can produce

coatings on 14" substrates. The zirconia-silica system is one which many companies have tried and abandoned, though TecOptics has had few problems. An advantage of these materials is a deposition temperature of 150°C, allowing lower stress coatings. A high oxygen partial pressure and 10-20 microns argon pressure are used during deposition.

Surface preparation is performed using conventional optical polishing. However, they are very aware of the effects surface quality has on deposited coatings. They place particular emphasis on the production of very fine surface structure coupled to a high optical figure. Typical values for their instrumentation are tolerances of $\lambda/200$, and large coated components have been made with less than $\lambda/30$ distortion. Characterization facilities are fairly limited. TecOptics performs the optical characterization in-house; damage threshold measurements are performed at the Rutherford Laboratory.

TecOptics is negotiating with Battelle to serve as their production outlet. A new facility in Richland, Washington will produce components designed by Battelle, incorporating sputtered coatings and diamond-turned substrates. Similar to their own products, the Battelle designs are high damage-threshold optics, though presumably of significantly larger size. While Battelle will develop new coatings and processes to be used at Richland, TecOptics intends to perform similar development, and is installing a sputter coater (14") at the Isle of Man facility. Other plans include work on the French multi-terawatt laser which is to be installed at the atomic energy laboratory at Limeil. Finally, an expanded characterization facility is in the works, and continued interaction with Rutherford Laboratory for damage threshold testing is expected.

SECTION III

THE PLACES WE MISSED

This section briefly reviews several organizations which were not visited during the survey. In some cases, the authors were already familiar with the activities of the group. Other organizations were discovered too late to allow a visit.

France

The Société Anonyme des Télécommunications (SAT) is a fairly large company located near Paris. Their specialty is IR reconnaissance systems, most of which are for the French Ministry of Defense. They also produce HgCdTe detectors, CO_2 lasers, and optical components. SAT makes IR thin films for their own use, but does not sell coatings per se (except in unusual circumstances).

Métallisations et Traitements Optiques (MTO) is the primary French competitor to Matra. They provide an optical coating service which is popular among optical component companies both in France and in other European countries.

The atomic energy laboratory at Limeil is performing high-power laser damage tests of optical thin films and components. Matra's coatings are tested at Limeil, and other French university and commercial groups are working with the laboratory.

Germany

The Physics Institute of the University of Düsseldorf is studying roughness of optical glass surfaces. They have reduced the rms roughness to less than 10 Å.

The laser group of the Max Planck Institute in Garching, near Munich, is performing high-energy tests of laser damage thresholds. They have a powerful iodine laser which could be used for testing the new coatings being developed in the US.

The Hochschule der Wehrmacht has developed a depth-resolved technique for photoacoustic spectroscopy. The research is in conjunction with that of the Fraunhofer Institute in Freiberg.

Israel

Dr. Y. Zerem of the Jerusalem College of Technology holds a low-cost grant from EOARD for the design of iodine laser coatings. Dr. Zerem spent some time working with the University of Dayton Research Institute at the Materials Lab, AFWAL.

The Technion is studying thin film parameters (absorption, refractive index, and thickness) for 10 micron window coatings. Their techniques include standard interferometry, an interferometric method for measuring ellipsometric phase shifts and amplitude variation, and absorption measurements in weakly absorbing thin films.

The Netherlands

The Technical University of Delft has a large optics program, including some laser projects and a thin films group. They fabricate laser coatings for their own use and for other laboratories, such as the University of Twente.

United Kingdom

Several commercial coating groups are producing optical thin films. Perhaps the most familiar of these is OCLI (Scotland), which has its own development group despite being a subsidiary of OCLI in Santa Rosa, CA. They provide high energy laser coatings, low scatter ring-laser mirrors, and infrared coatings to several European laboratories.

Another familiar name is Ealing Beck Ltd., a subsidiary of the Ealing Corporation in South Natick, MA. They have developed an aspheric generating machine for diamond-turned mirrors. Many of these components are produced for the Dynamics Group of British Aerospace.

Davin Optical Ltd. specializes in visible and IR components and night vision systems. They produce copper-nickel CO_2 laser mirrors (uncoated), or gold-coated ZnSe windows and lenses, and Ge components for the 3-14 micron range. Damage thresholds for microsecond pulses are approximately 50 MW/cm^2. The ZnSe and Ge are available with thin film coatings, though these might not be produced in-house.

Specac-Analytical Accessories Ltd. produces components for the UV through the IR. They also market interferometer systems and laser optics. Thin films are available for all parts of the spectral range for which they sell components.

Grubb-Parsons produces optical filters, laser mirrors, and beam splitters, and provides an optical coating service. Mirrors and laser coatings are available from 400 nm to 10.6 microns. Non-laser coatings can be custom produced for wavelengths as long as 20 microns. Hard high-reflectivity and AR coatings are also available.

Spectron Optical Coatings Ltd. is one of three companies which make up the Spectron Optical Holding Group. Almost all their effort goes into production, rather than development. Their products are mostly for the IR region; thin films are deposited on Ge and ZnSe, as well as visible wavelength glasses. Most of the coatings are tested to military specifications for humidity, abrasion, and adhesion. Special high-durability AR coatings on Ge are also subjected to salt-spray and temperature testing.

Astron Developments Ltd. sells superpolished substrates for optical and x-ray systems. They apparently do no optical coating work of their own, but supply uncoated components to groups working on ultra-low scatter laser mirrors and x-ray optics.

Academic groups working on thin films include the University of York, Loughborough University of Technology, and the University of Sussex. Professor O. Heavens at the University of York conducted much of the early research on multilayer coatings. The thin film and surface physics group is now led by Professor M. Prutton. Their primary emphasis is on studies of the initial stages of thin film growth and of the coating/substrate interface. Characterization methods include low energy electron diffraction, reflection high energy electron diffraction, and Auger spectroscopy.

The optics group at the Loughborough University of Technology is working on reactive ion plating of oxides, plasma deposition of carbon films, and laser damage in IR materials. The oxide films are produced by reactive magnetron sputtering or reactive evaporation,

with the ion-plating effect produced by an rf plasma. The research on carbon films studies the growth, structure, and optical properties as a function of the rf power, gas pressure, and hydrocarbon employed. Results of their experiments indicate that the optical properties are not strongly dependent on these factors, but that growth rate is a function of all these parameters.

Professor L. Holland of the University of Sussex is also working on carbon films. He is depositing amorphous carbon on germanium substrates using a plasma dissociation technique. Starting materials are hydrocarbons and fluorocarbons. Other research topics include reactive sputtering of metals in oxygen atmospheres, and rf sputtering of dielectric materials.

The Royal Signals and Radar Establishment is the driving force behind carbon-film research in the UK. Dr. A. Lettington is producing low stress, low absorption carbon layers using a dc glow discharge. He hopes to use such films for 45° angle of incidence mirrors, and for high efficiency AR coatings.

The National Physical Laboratory, which is Britain's equivalent of the National Bureau of Standards, does a lot of work on development of standards and measurement of optical and mechanical properties of thin films. They also grow a limited number of optical thin films, but only those which cannot be found elsewhere. Some recent examples include AR coatings for applications requiring a 45° angle of incidence, enhanced internal reflectors (Al_2O_3 - Ag - Al_2O_3 sandwiches) and protected UV mirrors. NPL provides a coating service (for their limited range) to industry and government laboratories.

The laser fusion section of the Atomic Weapons Research Establishment at Aldermaston is producing high efficiency AR coatings for their high energy laser (Nd:YAG?) system. They have developed a sensitive dc method for optical monitoring of film growth using a filtered light-emitting diode source and a PIN diode detector. AWRE is studying laser damage and propagation of CO_2 laser pulses, and they are very interested in laser-damage resistant coatings. This last area is also of concern to the Rutherford Laboratory, which is studying high energy lasers. The Rutherford Laboratory buys many of their damage resistant coatings from TecOptics and from the Queen's University of Belfast.

The center for measurements of laser damage thresholds is the General Electric Company (GEC) Ltd.'s Hirst Research Center. Many of the thin films groups in the UK provide samples to GEC for testing on their CO_2 and Nd:YAG systems.

This is still not an exhaustive list, but is based on our contacts within the European thin films community. Some of the groups mentioned probably deserve a follow-up visit.

SECTION IV

THE MOST SIGNIFICANT ACTIVITIES

This section reviews those groups that we visited that are most likely to have an impact on DOD thin film programs. For details we refer you to Sections II and III and the trip reports.

Coating development and production. There are several European companies and laboratories which are producing high quality coatings for various applications: Balzers (ultra-low scatter coatings), Barr & Stroud (hard coatings), the University of Hannover (UV, high energy laser, and ultra-low scatter coatings), Matra Optique (high energy laser coatings), Queen's University Belfast (high energy laser and UV coatings), and TecOptics (high energy laser coatings).

Thin film research. Two universities have programs on the basic physics and materials science of thin films: the Center for Thin Film Studies at the University of Aix-Marseille, and the University of Hannover.

Substrate preparation. Four groups are leading the effort in preparation of substrates and optical surfaces: the University of Århus (ion-implantation of laser mirrors), Balzers (superpolishing), Philips (single point turning of glasses), and REOSC (polishing of large optics).

Characterization. The University of Aix-Marseille makes sophisticated scattering measurements, sometimes using photon counting techniques. The Fraunhofer Institute in Freiberg has a wide range

of thin film characterization techniques, as does the University of Pierre and Marie Curie. Another Paris university (Orsay campus) concentrates on surface characterization. The Queen's University in Belfast has automated much of their optical characterization equipment and has developed a visible ellipsometer which does not utilize phase plates.

Process development. Many of the coating production groups are working on new processes for deposition of their thin films. The work is most concentrated at Balzers and Leybold-Heraeus, where the processes are licensed to buyers of their deposition equipment. The only "revolutionary" work is on the sputter-arc process at the State University of Mons.

Deposition equipment. Both Balzers and Leybold-Heraeus offer a wide range of equipment employing a variety of deposition techniques: thermal and electron-beam evaporation and sputtering systems. In addition, the systems are well-instrumented and most include computer controls which allow unattended deposition of multilayer coatings.

SECTION V

EUROPEAN VS. US TECHNOLOGY

This is necessarily a somewhat one-sided view, since we have seen most of the European activities at first-hand, and have only indirect information on US capabilities. Nevertheless, we feel that the following statements are probably close to the truth; the reader can make his or her own judgement.

European equipment for thin film deposition is quite advanced, probably comparable (perhaps superior) to anything available in the US. Much of the basis for this rests on the use of software to control the entire deposition process. Such automation removes, to a significant extent, the role of variations between technicians and the resulting variability in the quality of the coatings. System hardware also contributes to the quality of the equipment.

Some very high quality coatings are available from European groups. Of most value to DOD systems are low scatter coatings, carbon coatings, and abrasion-resistant coatings. On the other hand, Europe cannot compete with the US in the area of high energy laser coatings -- the demand for high damage-threshold optics in Europe is negligible compared to the US. Only one company specializes in such coatings: TecOptics. Their cooperation with Battelle in the States on research and production of these coatings should be mutually beneficial to both groups.

Characterization, both optical and structural, is fairly good, but we saw nothing much different from that done in the States, with the possible exception of attenuated total reflectivity and nuclear analysis techniques. Materials research is at a low level, though nearly everyone who uses ThF_4 would like to find a substitute. The majority of the groups we visited buy materials from Merck, the German chemical company.

Surface preparation technology is following in the footsteps of US groups, especially in the area of diamond-turning. The two areas which may represent work unique to Europe are the single-point turning of optical glass at Philips and the flexible-tool polishing of large optics at REOSC.

Some of the basic research on thin film growth may prove to be quite valuable, especially that work being performed by the group at the University of Aix-Marseille. We have no data on which to make a comparison, but their efforts at producing thin film coatings which differ from theory by only 10^{-6} would be a large step towards making thin film deposition less of an art and more of a science.

SECTION VI

RECOMMENDATIONS

We have visited many thin films groups throughout Europe and have identified quite a few more which should be of interest to the DOD. However, we were probably not sufficiently familiar with the subject to always ask the right questions of the people we visited. Our primary recommendation is, therefore, that a team of thin films/surfaces experts, assembled from the appropriate DOD organizations, visit some of the groups mentioned in this report. The purpose of such an experts team would be to discuss, at a detailed level, the programs being conducted by the various European organizations, to identify the groups that can contribute to US programs, and to determine with which groups some cooperative efforts might be initiated.

At a minimum, we suggest that representatives of the AFWL, NWC, and Materials and Avionics Laboratories be selected for such a team. While a detailed itinerary cannot be produced at this time, there are definitely some organizations which should be included. These are Balzers, Barr & Stroud, the Center for the Study of Thin Films at the University of Aix-Marseille, Leybold-Heraeus, Matra, [illegible]optics, and the Technical University of Hannover. Other possibilities include the Fraunhofer Institute, Philips, Queen's University Belfast, and REOSC. Of course, the team may wish to split up to review different organizations related to a particular subject. In any event, a two-week trip should be planned, with some time set aside at EOARD after

the visits for the writing and editing of an assessment report. (We have found this to be the only way to produce such a document in cases where the authors come from several geographically separate locations.)

Since some of the organizations we didn't visit may be worthwhile for the experts team, we also recommend that Captain Tom Humpherys, who will be the new Chief of Physics at EOARD as of August 1981, should make a preliminary visit to some of those groups which he feels may contribute to the experts team visit. (Captain Mardiguian will leave EOARD in mid-June, but may be contacted at the Department of Physics, USAF Academy, CO 80840 (AV 259-3510) should any specific questions arise. Trip reports should be requested directly from EOARD.)

The European organizations we visited were, in general, very willing to discuss their programs and, in many cases, their plans. The experts team should be prepared to reciprocate through discussion and briefings to whatever extent is possible.

APPENDIX A

ORGANIZATIONS: ADDRESSES AND POINTS OF CONTACT

AGA Optical AB Box 2076 S-18302 Täby, Sweden (8) 768-0980	Dr. R. Jacobsson, President
Centre d'Etudes des Couches Minces Ecole Nationale Supérieure de Physique Domaine Universitaire de Saint-Jérome (University of Aix-Marseille III) Rue Henri Poincaré 13397 Marseille Cedex 4, France (91) 989010	Dr. E. Pelletier
University of Århus Institute of Physics DK-8000 Århus-C, Denmark (6) 128899	Dr. G. Sørensen
Astron Developments Ltd. 2 Park Street Teddington, Middlesex TW11 0LT, England (1) 977-9306	
Atomic Weapons Research Establishment Aldermaston Reading, Berkshire RG7 4PR, England (7356) 4111	Mr. P. W. King
Balzers AG für Hochvakuumtechnik und Dünne Schichte FL-9496 Balzers Principality of Liechtenstein (75) 44111	Dr. E. Ritter, Head, Thin Films Division Dr. K. H. Guenther, Head, Thin Film Quality Assurance Dept Dr. W. Thoeni, Head, Thin Film Development
Barr & Stroud Ltd. Caxton Street Anniesland, Glasgow G13 1HZ, Scotland (41) 954-9601	Dr. B. Monachan, coating research group
Battelle Geneva Research Center 7, route de Drize CH-1227 Carouge/Geneva, Switzerland (22) 439831	Dr. B. Zega, sputtering techniques

CIT-Alcatel
Division Vide et Mécanique
33, rue Emeriau
75725 Paris, Cedex 15, France
(1) 578-6165

Mr. J.-J. Bessot, Head, Thin Films Department

Commissariat à l'Energie Atomique
Centre d'Etudes de Limeil
B.P. No. 27
94190 Villeneuve St. Georges, France
(1) 569-9660

Davin Optical Ltd.
13 Alston Works
Alston Road
Barnet, Hertfordshire EN5 4EL, England
W1) 440-9354

Technische Hogeschool Delft
Department of Applied Physics
Julianalaan 134
Delft, The Netherlands
(15) 789111

Prof. H. J. Frankena

Universität Düsseldorf
Physikalisches Institut
Universitätstrasse 1
D-4000 Düsseldorf 1
Federal Republic of Germany
(211) 3111

Prof. J. Bodesheim
Dr. A. Otto

Ealing Beck Ltd.
Greycaine Road
Watford, Hertfordshire WD2 4PW, England
(1) 924-2261

Ferranti Ltd.
Professional Components Department
Dunsinane Avenue
Dundee DD2 3PN, Scotland
(382) 89321

Mr. N. Forbes, Product Manager, Lasers

Fraunhofer Institut für Angewandte Festkörperphysik
Eckerstrasse 4
D-7800 Freiburg-im-Breisgau
Federal Republic of Germany
(761) 273091

Dr. P. Koidl, Head, Solid State Chemistry Department
Dr. A. Bubenzer, optical thin films

General Electric Company Ltd. Hirst Research Center East Lane Wembley, Middlesex HA9 6PP, England (1) 904-1262	Mr. R. M. Wood, laser damage testing
Grubb-Parsons Ltd. Walkergate Newcastle upon Tyne NE6 2YB, England (632) 650711	
Technische Universität Hannover Institut für Angewandte Physik Welfengarten 1 D-3000 Hannover Federal Republic of Germany (511) 762-2452	Dr. J. Ebert
Hochschule der Wehrmacht Munich (no address found) Federal Republic of Germany	Prof. G. Busse
Institutet för Optisk Forskning Lindstedtsvägen 24 S-10044 Stockholm, Sweden (8) 787-7282	Dr. L. Stensland
Jerusalem College of Technology Department of Physics and Electronics 21 Havaad Haleumi Street P.O. Box 16031 Jerusalem, Israel (2) 423131	Dr. Y. Zerem
Division Jobin-Yvon Instruments S.A. 16-18 rue du Canal 91160 Longjumeau, France (1) 909-3493	Mr. B. Touzet, Director, Monochromator Systems
Ernst Leitz Wetzlar GmbH Optical Works Ernst-Leitz-Strasse D-6330 Wetzlar Federal Republic of Germany (6441) 291	Mr. R. Ludwig, Head, Thin Film and Filter Laboratory

Leybold-Heraeus GmbH
Vacuum Process Engineering Division
Wilhelm-Rohn-Strasse 25
D-6450 Hanau 1
Federal Republic of Germany
(6181) 364616

Dr. W.-D. Münz, Manager, Coating R&D Department
Dr. H. Schwiecker, optical coating processes

Loughborough University of Technology
Department of Physics
Ashby Road
Loughborough, Leicestershire LE11 3TU
England
(509) 63171

Dr. D. C. Emmony
Dr. R. P. Howson

Matra
Division Optique
93, avenue Victor Hugo
B.P. 209
92505 Rueil-Malmaison Cedex, France
(1) 749-0345

Mr. J. Guerain, Manager, Optics and Coating
Dr. J. Charlier

Max Planck Institute for Quantum Optics
D-8046 Garching-bei-München
Federal Republic of Germany
(89) 32991

Prof. K. L. Kompa

Métallisations et Traitements Optiques
11 rue Ampère
B.P. 6
91302 Massy Cedex, France
(1) 920-6307

Mr. G. Vieux

Université de l'Etat à Mons
Faculté des Sciences
Avenue Maistriau, 23
7000 Mons, Belgium
(65) 315171

Prof. J. van Cakenberghe

National Physical Laboratory
Division of Mechanical and Optical Metrology
Queens Road
Teddington, Middlesex TW11 OLW, England
(1) 977-3222

Dr. R. J. King, Head, Optical Standards and Fine Measurement

Newcastle upon Tyne Polytechnic
Department of Physics and Physical Electronics
Newcastle upon Tyne, NE1 8ST, England
(632) 26002

Dr. M. Bowden
Dr. R. Hill

OCLI Optical Coatings Ltd. Hillend Industrial Estate Dunfermline KY11 5JE, Scotland (383) 823631	Dr. T. Christmas
NV Optische Industrie de Oude Delft van Miereveltlaan 9 2612 XE Delft, The Netherlands (15) 132923	Dr. H. Mulder, Head, Research Dept Dr. A. J. Vermeulen
Optisk Laboratorium 100 Lundtoftevej, Bldg 307 DK-2800 Lyngby, Denmark (2) 883848	Mr. W. Olsen, Director
Queen's University of Belfast Department of Pure and Applied Physics Belfast BT7 1NN, Northern Ireland (232) 45133	Prof. P. H. Lissberger
Université de Paris Sud Institut d'Optique Bâtiment 503, Centre d'Orsay 91405 Orsay Cedex, France (6) 941-7269	Dr. P. Croce
NV Philips Gloeilampenfabrieken Department of Military Affairs Eindhoven, The Netherlands (40) 783666	Mr. J. van Zanten Dr. J. Haisma (Philips Research Laboratories)
Université Pierre et Marie Curie Laboratoire d'Optique des Solides 75230 Paris Cedex 05, France (1) 336-2525	Prof. F. Abelès
REOSC Optique 10 rue des Ecoles Ballainvilliers 91160 Longjumeau, France (1) 448-8875	Mr. J. Espiard, Assistant Director General
Optische Werke G. Rodenstock POB 140440, Isartalstrasse 43 D-8000 Munich 5 Federal Republic of Germany (89) 720-2429	Dr. P. Kuttner, Manager, R&D, Precision Optics Division

Royal Signals and Radar Establishment St. Andrews Road Great Malvern, Worcestershire WR14 3PS England (6845) 2733	Dr. A. Lettington
Société Anonyme des Télécommunications 19 rue de la Gare 94230 Cachan, France (1) 582-3111	Mr. Y. Touze
Specac Analytical Accessories Ltd. Unit 3, Lagoon Road St. Mary Cray Orpington, Kent BR5 3QX, England (689) 73134	
Spectron Optical Coatings Ltd. Ashville Trading Estate Nuffield Way Abingdon, Oxfordshire OX14 1TD England (235) 28212	
University of Sussex Unit for Plasma Materials Processing Falmer, Brighton, Sussex BN1 9QH England (273) 66755	Prof. L. Holland
Technical Optics Ltd. Second Avenue Onchan, Isle of Man British Isles (624) 4443	Mr. D. L. Hunt, Director
Technion Department of Electrical Engineering Haifa 32000, Israel (4) 292111	Dr. J. Shamir
Technische Universität Wien Institut für Physikalische Elektronik Gusshausstrasse 25 A-1040 Vienna, Austria (222) 653785	Prof. A. J. Schmidt

APPENDIX B

TRIP REPORTS/MEMOS FOR THE RECORD

The following trip reports and memos may provide additional information on some of the groups we visited. You may request copies from

EOARD/LNP
Box 14
FPO NY 09510

Please specify organization and date of visit.

Organization	Date of Visit	EOARD Visitor
AGA Optical AB	6 Apr 1981	Mardiguian
University of Århus	10 Apr 1981	Mardiguian
University of Aix-Marseille III	21 Apr 1981	Mardiguian
Balzers AG	11 Feb 1981	Mardiguian
Barr & Stroud Ltd.	10 Dec 1980	Mardiguian
Battelle Geneva Research Center	13 Feb 1981	Mardiguian
CIT-ALCATEL	29 Apr 1981	Mardiguian
Ferranti Ltd.	9 Dec 1980	Mardiguian
Fraunhofer Institute for Applied Solid State Physics	20 Mar 1981	Fenner/Mardiguian
Technical University of Hannover	25 Mar 1981	Mardiguian
Institute for Optical Research	7 Apr 1981	Mardiguian
Jobin-Yvon	28 Apr 1981	Mardiguian
Ernst Leitz Wetzlar GmbH	18 Mar 1981	Fenner/Mardiguian
Leybold-Heraeus GmbH	19 Mar 1981	Fenner/Mardiguian

Matra Optique	24 Apr 1981	Mardiguian
State University of Mons	30 Apr 1981	Mardiguian
Newcastle upon Tyne Polytechnic	8 Dec 1980	Mardiguian
NV Optische Werke De Oude Delft	14 Apr 1981	Mardiguian
Optisk Laboratorium	9 Apr 1981	Mardiguian
Queen's University of Belfast	24-25 Nov 1980	Mardiguian
University of Paris-South	27 Apr 1981	Mardiguian
Philips Research Laboratories	13 Apr 1981	Mardiguian
University of Pierre and Marie Curie	23 Apr 1981	Mardiguian
REOSC Optique	28 Apr 1981	Mardiguian
Optische Werke G. Rodenstock	24 Mar 1981	Mardiguian
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Technical Optics Ltd.	26 Nov 1980	Mardiguian
Technical University of Vienna	9 Feb 1981	Mardiguian

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